静止衛星を用いた同期CDMA通信システムにおける同期化手法に関する検討

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あらまし: 光ファイバを用いた高速コアネットワークは既に全国に敷設されているが, 山間, 離島などからコアネットワークへアクセスすることは依然として難しいのが現状である. この問題を解決するためにブロードバンドネットワークへの遠隔僻地からのアクセス系として静止衛星を用いた同期 CDMA (Code Division Multiple Access) 通信システムを取り上げ検討を行う. 静止衛星を用いた通信システムは広範なサービスエリアを有し, 同期 CDMA 方式をパケットベースのネットワークへの多元接続方式として用いることで統計的多重効果により電力, 周波数の有効利用が図れる. 同期 CDMA 通信システムは各信号の送信タイミングを適切に制御することで受信点で完全に同期させる必要がある. その際, 高速通信を実現するためにはチップレートを十分に高くする必要がある為, 高い同期精度が必要となる. 本論文では制御局からの制御信号及び自局信号の受信タイミングから信号送出タイミングを決定する手法について検討を行う. まず, 固定フィルタやカルマンフィルタの持つ問題点を指摘する. 次に, 観測雑音やトレンド成分に対してロバストな特性を持つ提案手法を紹介し, その同期精度を定量的に評価する. その結果, 提案手法を用いることで 1Gchip/sec の同期 CDMA 通信システムが実現可能となることを示す.

キーワード: 同期 CDMA 通信システム, 静止衛星通信, 同期化手法, カルマンフィルタ, 遅延揺らぎ, 予測フィルタ

A Synchronization Method for Synchronous CDMA Systems with GEO Satellites

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Abstract: High-speed core networks with optical fibers are globally being installed. However, it is very difficult to access these core networks from rural districts such as remote places among mountains and solitary islands. Synchronous CDMA systems with GEO satellite links are very attractive to solve this problem, since such systems have wide service areas and are suitable for packet-based networks due to their statistically multiplexing effect. Furthermore, their statistically multiplexing effect leads to effective frequency and power efficiency. In synchronous CDMA systems, each transmitted signal from a fixed earth station must be controlled to be synchronized with each other. However, the broadband systems require extremely precise timing control. In this paper, we discuss synchronization methods and evaluate their timing accuracy for the broadband systems quantitatively. First, we point out defects of two fixed filter methods and a Kalman filter method. Then, we propose a new synchronization method, which is robust to random noise and trend components. As a result, we conclude that the proposed synchronization method can make it possible to synchronize 1Gchip/sec CDMA systems with GEO satellites.

keywords: synchronous CDMA system, GEO satellite link, synchronization method, Kalman filter, scintillation of delay time, estimation filter

1 Introduction

The asynchronous transfer mode (ATM), which transfers data in fixed size packets called ATM cells, attracts a great deal of attention as a communication method in multimedia networks. ATM core networks with optical fibers are already globally operated. However, it is very difficult to access these core networks from rural districts such as remote places among mountains and solitary islands. GEO satellite communication systems provide a solution to connect rural areas with ATM core networks due to their wide service areas. When multiple fixed earth stations access a GEO satellite, GEO satellite communication systems require the technique of multiple access. CDMA systems are suitable for packet-based networks due to their statistically multiplexing effect. However, conventional asynchronous CDMA systems have substantial lower frequency efficiency than fundamental orthogonal multiple access methods such as TDMA and FDMA. In order to overcome this drawback, we consider to apply synchronous CDMA for GEO satellite communication systems. In synchronous CDMA systems, each transmitted signal from a fixed earth station must be controlled to be synchronized with each other. Furthermore, the broadband systems require extremely precise timing control. In this paper, we discuss synchronization methods and evaluate their timing accuracy quantitatively. The most of conventional synchronization methods utilize fixed filters. However, the accuracy of them is not satisfactory for broadband communications. Furthermore, these studies consider only simple waveforms as delay scintillations. First of all, we generate virtual signals of delay scintillations based on the characteristic of the propagation media and noises. Secondly, we point out defects of fixed filter methods and a Kalman filter method using the signals generated as described above. Thirdly, we propose a new synchronization algorithm, which has robustness to observation noise and trend components. As a result, we clarify that our synchronization method can make it possible to synchronize 1Gchip/sec CDMA communication systems with GEO satellites.

2 System Model

In this section, we describe our system model. Figure 1 illustrates a system model used in this paper. In this paper we assume a direct sequence CDMA system using Ka band and its chip-rate of 1Gchip/sec. One of spreading codes is assigned to the NCS (Network Control Station) and the other are assigned to FESs (Fixed Earth Stations). Every FES can access core networks via a gateway which is connected with the NCS. It is well-known that synchronous CDMA systems have good performance only if the synchronization accuracy is within 0.3 of chip duration [1]. Consequently, we should achieve the synchronization accuracy of 0.3chip/sec. Besides let us assume that the number of satellite beams is one and each FES receives its own signal and a pilot signal transmitted from NCS.

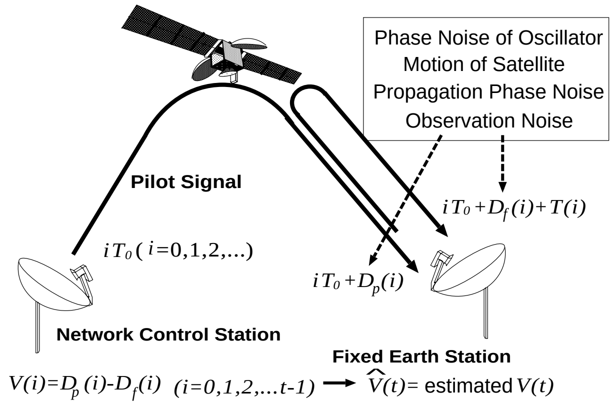

Figure 1: System model of a synchronous CDMA communication system with a GEO satellite.

Figure 2 illustrates a block diagram of a receiver and a transmitter in FESs. Figure 3 illustrates the outline of computer simulation in this paper. Each FES measures the i-th delay time of a pilot signal $D_{\mathrm{p}}(i)$ and the i-th delay time of its own signal $D_{\mathrm{f}}(i)$ every $T_0 = 1.0$sec with delay locked loops in Timing Detectors in Fig. 2. We define the i-th delay difference as $V(i) = D_{\mathrm{p}}(i) - D_{\mathrm{f}}(i)$. Each signal synchronizes with each other in the system by setting $T(t) = \hat{V}_t$, where $T(t)$ is the t-th timing of signal transmitting and $\hat{V}_t$ is estimated $V(t)$ using $V(i)$ $(i = 0, \cdots, t-1)$. The transmitting time of signals $T(t)$ is renewed periodically. The signal processing unit in Fig. 2 computes $\hat{V}_{t+1}$. Figure 4 illustrates synchronization sequence. In this paper, we focus our interests on the methods of $V(i)$ estimation.

We assume that a satellite is located at 132 degrees, east longitude with eccentricity of 0.0005, orbital inclination angle of 0.05°and also assume that NCS is allocated in the center of Tokyo.

3 Delay Scintillation Model

In this chapter we discuss propagation characteristics which should be taken into account in order to evaluate the accuracy of synchronization in the system. The delay difference $V(i)$ is characterized by

1. a motion of a satellite,
2. a phase noise of an oscillator,
3. a propagation phase noise (in the troposphere) and
4. an observation noise.

The delay scintillation caused by the motion of a satellite is expressed as

$$s_{\text{sat}}(t) = A_{\text{sat}} \sin(\omega t + \phi), \tag{1}$$

where $\omega = 2\pi/(24 \times 60 \times 60)$rad/sec and A_{sat} varies with the location of FES, which is at most 3618nsec in Japan. The effects except for the motion of satellite are expressed as random signals, whose power spectrum is known. The effect of the observation noise is expressed as white Gaussian noise with standard deviation σ_v. We utilize the measured spectrum of an Italsat beacon signal [2] as effects of oscillator phase noise and a propagation phase noise.

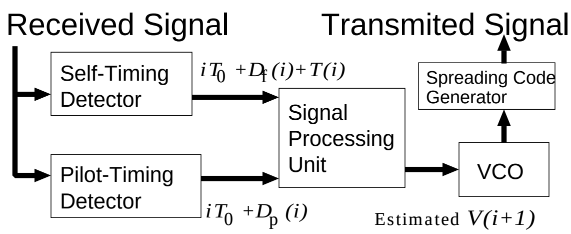

Figure 2: Block diagram of a receiver and a transmitter.

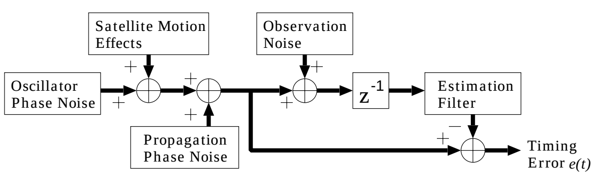

Figure 3: Procedure of computer simulation.

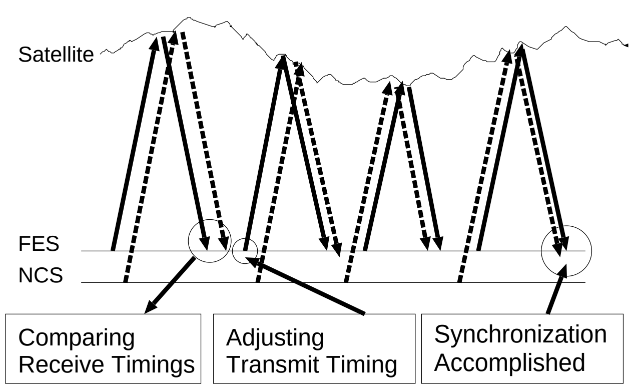

Figure 4: Outline of a synchronization sequence.

4 Estimation Methods

4.1 Fixed filter methods

We examine the following two fixed filters as estimation methods.

$$F_1(z) = \frac{2z^{-1} - z^{-2}}{1 - 2z^{-1} + z^{-2}} \tag{2}$$

$$F_2(z) = \frac{1}{4} \cdot \frac{2z^{-1} - z^{-2}}{1 - 2z^{-1} + z^{-2}} \tag{3}$$

$F_1(z)$ is known as an optimum filter, so it minimizes a mean square error in the condition that the target signal is a parabolic signal. $F_2(z)$ is a filter whose gain is smaller than that of $F_1(z)$, which has robustness in case that observation noise can not be neglected.

4.2 The Kalman Filter Method

The Kalman filter is an online algorithm which estimates the states of systems iteratively. It is the optimum filter on the condition that

1. linearity of a system equation,
2. whiteness of system and observation noise,
3. Gaussian noise and,
4. the least quadratic criteria

are satisfied. Suppose the system generating $V(t)$ is represented as

$$\boldsymbol{x}_{t+1} = F\boldsymbol{x}_t + G\boldsymbol{w}_t \tag{4}$$

$$V(t) = H\boldsymbol{x}_t + \boldsymbol{v}_t, \tag{5}$$

where $\boldsymbol{x}_t$ is a 3-dimensional state vector, $\boldsymbol{w}_t$ is a 1-dimensional plant noise vector, $\boldsymbol{v}_t$ is a 1-dimensional observation noise vector, F is a 3×3 state transition matrix, G is a 3×1 driving matrix and H is a 1×3 observation matrix. Also, we assume that $\boldsymbol{w}_t$ and $\boldsymbol{v}_t$ are 1-dimensional white Gaussian noise vectors, whose means are equal to 0 and whose covariance matrix is expressed as

$$E\left\{ \begin{bmatrix} \boldsymbol{w}_t \\ \boldsymbol{v}_t \end{bmatrix} \begin{bmatrix} \boldsymbol{w}_s^{\mathrm{T}} & \boldsymbol{v}_s^{\mathrm{T}} \end{bmatrix} \right\} = \begin{bmatrix} Q & S \\ S^{\mathrm{T}} & R \end{bmatrix} \delta_{ts}. \tag{6}$$

where Q is a 1×1 non-negative constant symmetrical matrix, and R is a 1×1 positive constant symmetrical matrix. We assume $S = 0$ in the system because of its nature. Besides the initial state $\boldsymbol{x}_0$ obeys the normal distribution with a mean

$$E\{\boldsymbol{x}_0\} = \overline{\boldsymbol{x}}_0 \tag{7}$$

and a covariance matrix

$$E\{[\boldsymbol{x}_0 - \overline{\boldsymbol{x}}_0][\boldsymbol{x}_0 - \overline{\boldsymbol{x}}_0]^{\mathrm{T}}\} = \Sigma_0. \tag{8}$$

Let us assume that $V(t)$ is represented as the output of an auto regressive (AR) equation of the 3rd order. This means that $V(t)$ is an output of a linear system. This is because that a unique linear system is derived by an

AR equation. The N-th order AR equation in a general form is represented as

$$x_t + \sum_{m=1}^{N} a_m x_{t-m} = W_t, \qquad (9)$$

where W_t is a white Gaussian noise with a standard deviation σ_w. The set of coefficients a_i is equal to the impulse response which whitens the spectrum of x_i.

Under the above-mentioned assumption, the Kalman fileter is represented as

$$\begin{aligned}
\hat{\boldsymbol{x}}_{t+1/t} &= F\hat{\boldsymbol{x}}_{t/t}, && (10)\\
\hat{\boldsymbol{x}}_{t/t} &= \hat{\boldsymbol{x}}_{t/t-1} + K_t[V(t) - H\hat{\boldsymbol{x}}_{t/t-1}], && (11)\\
K_t &= P_{t/t-1}H^{\mathrm{T}}[HP_{t/t-1}H^{\mathrm{T}} + R]^{-1}, && (12)\\
P_{t+1/t} &= FP_{t/t}F^{\mathrm{T}} + GQG^{\mathrm{T}}, && (13)\\
P_{t/t} &= P_{t/t-1} - K_tHP_{t/t-1}, && (14)\\
\hat{\boldsymbol{x}}_{0/-1} &= \overline{\boldsymbol{x}}_0, && (15)\\
P_{0/-1} &= \Sigma_0, && (16)\\
& && (17)
\end{aligned}$$

where $\hat{\boldsymbol{x}}_{t_1/t_2}$ is estimated state vector $\boldsymbol{x}_{t_1}$ using $V(t)$ $(t < t_2)$. This procedure is computed iteratively.

Then, $\hat{V}(t)$, which is the estimation of $V(t)$, is derived as

$$\hat{V}(t) = HF\hat{x}_{t/t}. \qquad (18)$$

Figure 5 illustrates a block diagram to estimate $V(t)$ using Kalman filter.

5 Synchronization Accuracy

In this section, we examine the synchronization accuracy of signals from a FES and a NCS by computer simulations. The estimated parameters of AR-equation are derived as $a_1 = -1.644964$, $a_2 = 0.487694$ and $a_3 = 0.156907$ for the maximum motion of a satellite in Japan. We estimate a delay scintillation using a Kalman filter of the 3rd order with these parameters. The effect of satellite motion, whose period is 1 day, can be approximately a ramp signal if it is observed in a span short enough compared with 1day.

We compute the distribution of the estimation error $e(t) = V(t) - \hat{V}(t)$. Supposing that $e(t)$ is expressed as an ergodic process, the probability density function (PDF) is gived as a distribution of sample processes. We set an observation time to 10,000sec. The PDF of error using each filter is shown in Fig. 6. In the figure the error of fixed filter methods spread widely. The accuracy of the F_1 filter method is very poor due to unstability against observation noise. Hence, we will not discuss the F_1 filter method in the following sections.

On the other hand, we observe a large offset of distribution in the Kalman filter method, because the Kalman filter underestimates the value. This results from the fact that the signal has a large trend component caused by an effect of satellite motion. The estimation of parameters of AR-equations is one of parametric power-spectrum estimations. So, large trend components such as the motion of a satellite cause aliasing components in all frequency. Therefore, an estimation of coefficients of AR-equations causes ambiguity of spectrum estimation in lower frequency. This is the reason of large offset of estimation error in the Kalman filter method. Consequently, we clarify that the estimation of Kalman filter is not accurate enough, although it has robustness against an observation noise. The root mean square (RMS) error using the Kalman filter method is 0.702nsec, which is larger than the aimed accuracy of 0.3nsec.

As a result, both of the fixed filter methods and the Kalman filter method have not enough performance to synchronize 1Gchip/sec CDMA systems with GEO satellites.

6 Proposed Algorithm and the Performance

6.1 Proposed algorithm

The problem we are facing is the defect of Kalman filter method. We propose a new algorithm in this section, in order to give a solution for the problems and improve the accuracy of synchronization. The proposed algorithm is a extension of the Kalman filter method. The proposed algorithm is as follows.

1. The regression line is computed by linearly fitting to the recent M data.
2. The value of the regression line is subtracted from $V(t-1)$ and the temporal estimated value is derived by applying the data to Kalman filter.
3. $\hat{V}(t)$ is obtained by the temporal value added to the value of regression line.

Moreover, we propose an interpolation method. Let us define $v(t)$ $(t \in \mathbf{R})$ as a generalized $V(i)$. The relation of them is as follows.

$$v(kT_0) = V(k) \qquad (19)$$

The interpolation of the estimated value for $kT_0 \leq t < (k+1)T_0$ is given as $v(t) = V(k) + a(t - kT_0)$, where a is an inclination of the regression line. An outline of the proposed algorithm is shown in Fig. 7. This procedure is repeated iteratively in the FES signal processing unit. This algorithm may have a good performance against a ramp signal such as trend component caused by a motion of a satellite, because the regression line expresses a large trend component effectively.

6.2 Parameter Optimization for Proposed Algorithm

In this subsection, we optimize the parameter M in the proposed algorithm. If M is small, the estimation of coefficients of a regression line becomes unstable, which results in bad accuracy of synchronization. On the other hand, if M is large, the approximation of linear change for a satellite motion is not true, which also cause a bad performance of synchronization. Moreover, because large M cause complexity of signal processing units and long computational time, it is desirable that M is as small as the performance of synchronization is sufficient. The relation of the RMS of an estimation error and M is shown in Fig. 8.

We select $M = 100$ based on the condition above and Fig. 8. Following discussions assume that $M = 100$.

6.3 The Accuracy of Synchronization Using Proposed Algorithm

PDF of an estimation error is shown as a real line in Fig. 9. Compared to simple Kalman filter, the proposed algorithm have very little offset of distribution of estimation error. Additionaly, the proposed algorithm has a better performance than that of fixed filter F_2, which has an unstability against an boservation noise. And, the RMS of estimation error using the proposed algorithm is 0.275, which is smaller than aimed accuracy of 0.3nsec.

7 Sensitivity of Synchronization Accuracy to Satellite Motion

In this section, we examine synchronization sensitivety in each method for the motion of the satellite on the condition of $\sigma_v = 0.5$nsec. We change the amplitude of the satellite motion effect and plot the RMS error of synchronization for each method in Fig. 10. The fixed filter method with F_2 has constant performance but the accuracy is not enough. The accuracy of Kalman filter method varies with the motion effect of the satellite. On the condition that the motion effect of the satellite can be neglected, the accuracy is approximately equal to

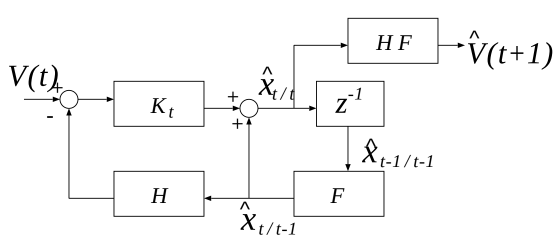

Figure 5: A block diagram of a method to estimate the next value of $V(t)$.

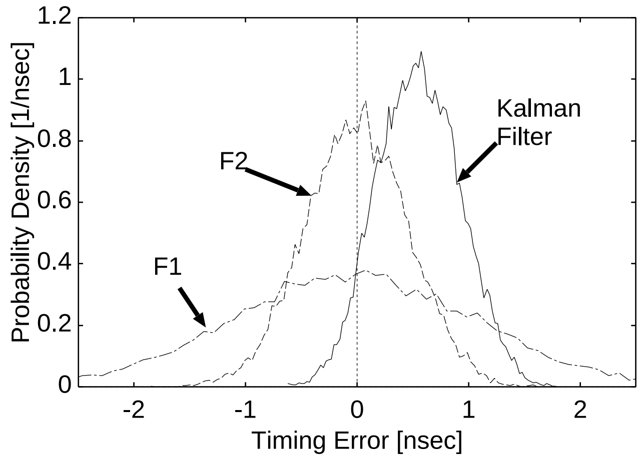

Figure 6: PDF of timing errors in three estimation methods using different filters.

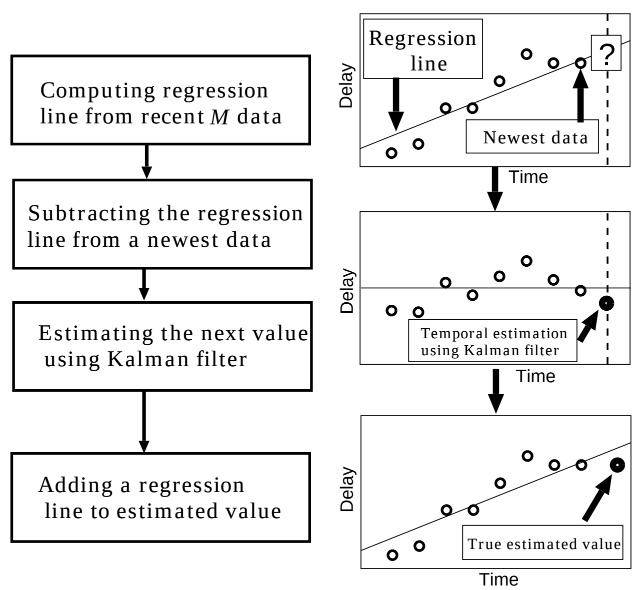

Figure 7: Proposed algorithm outline.

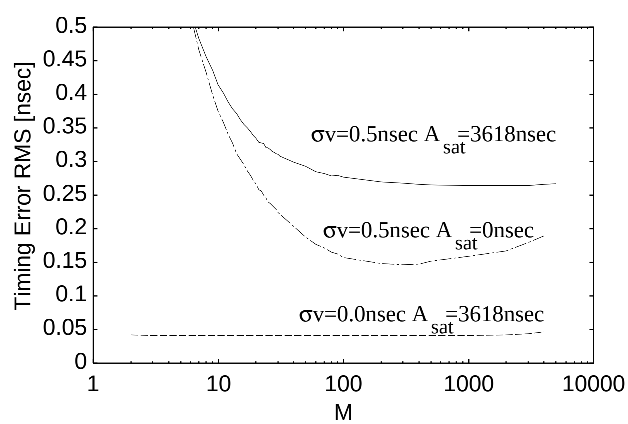

Figure 8: Relationship between RMS estimation errors and M.

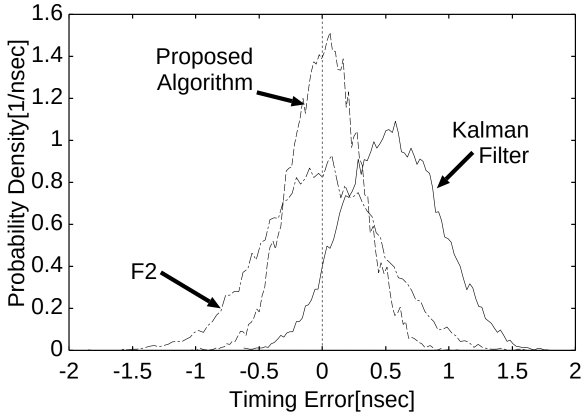

Figure 9: PDFs of estimation errors for various filters.

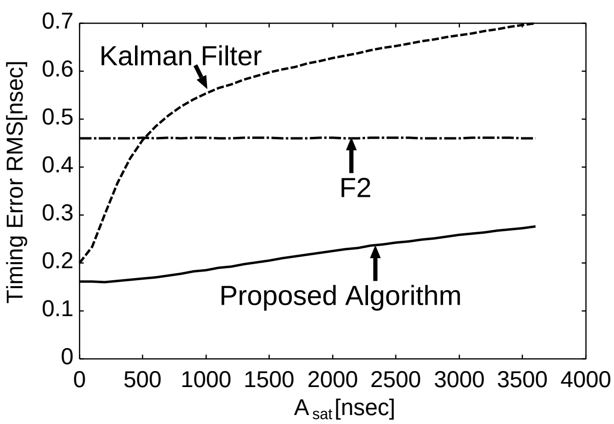

Figure 10: Relationship between RMS timing error and A_{sat} for each synchronization method.

that of the proposed method. However, the larger the motion effect of the satellite becomes, the poorer the accuracy of the synchronization becomes. The proposed algorithm has much better performance than these of the methods mentioned above, although it increases with a small inclination in accordance with the motion effect of the satellite.

8 Conclusion

In this paper, we proposed a new algorithm to synchronize synchronous CDMA systems with GEO satellites. Conventional synchronization methods such as a fixed filter or Kalman filter have an insufficient synchronization accuracies. It is clarified that the proposed algorithm can make up the defects of these filters and achieve an enough accuracy against the worst case in Japan.

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